

The Observational Approach in Rock Engineering.

“For a billion years, the patient earth amassed documents and inscribed them with signs and pictures which lay unnoticed and unused. Today, at last, they are waking up, because man has come to rouse them. Stones have begun to speak, because an ear is there to hear them. Layers become history and, released from the enchanted sleep of eternity, life’s motley, never- ending dance rises out of the black depths of the past into the light of the present.” Cloos. (1954)

.....

Rock variability and uncertainty as to the extent of the variability are important concerns in many aspects of geotechnical engineering. To address this issue in soil mechanics, Peck (1969) recommended the ‘Observational Approach’¹ The performance of an initial design is observed and then modified, progressively, as deemed appropriate to improve performance.

In rock engineering, perhaps the best example of the observational approach is the so-called *New Austrian Tunnelling Method*, or NATM.

The topic of tunnel support design was of considerable interest in Europe, especially in the 1930’s - 1960’s. Large inelastic deformation of soft shales in coal mines [Fenner (1938), Labasse (1949)], and driving of hard rock tunnels through high overburden in the Alps were serious problems.

Labasse (1949) described the practical problem as follows

*“First, **the types of support to be used must be limited to one or two** in order not to disrupt the material supply operations underground. This standardization makes precise calculation of a support for each section [of tunnel advance] useless. Further, the need to install the support immediately after excavation does not allow time to make calculations and fabricate the support. In order to arrive at a precise determination it would be necessary, in fact, to study each section separately because it would differ from neighboring sections with respect to the rock layers encountered, their dip and their disposition. It would be necessary to take a test specimen from each layer, determine its properties and the influence of these properties on neighboring layers. This would require a series of experiments and mathematical analyses whose solution, assuming that a solution is possible, would take up precious time during which the excavation would certainly have collapsed.”²*

Rabcewicz, aided by colleagues Müller and Pacher, introduced the notion of using **a support system that could be modified on site**, to suit the behavior of the rock as it was observed when exposed at the tunnel face. The essence of the method is described in the abstract to the Rabcewicz (1964) paper,

The New Austrian Tunnelling Method.

*After describing the influence of rock pressure effects on tunnel linings, the author underlines the inadequacy of conventional tunnel driving and lining methods in poor ground and explains the effectiveness and reliability of **a new method consisting of a thin sprayed concrete lining, closed at the earliest possible moment by an invert to a complete ring –called an “auxiliary arch” –the deformation of which is measured as a function of time until equilibrium is obtained.** Ways are*

¹ Also known as the “Design as you Go” approach. See also [https://en.wikipedia.org/wiki/Observational_method_\(geotechnics\)](https://en.wikipedia.org/wiki/Observational_method_(geotechnics))

² Translation from the original French.

shown to determine the magnitude of active forces, which leads to dimensioning of linings on an empirical basis*. Further articles describe successful application of the method.

*The substance of this series was originally presented at the XIII Colloquium of the International Society of Rock Mechanics in Salzburg, October 1962, and this English version, which contains additional material., is published by arrangement with Springer-Verlag, Vienna, the publishers of Felsmechanik und Ingenieurgeologie.³

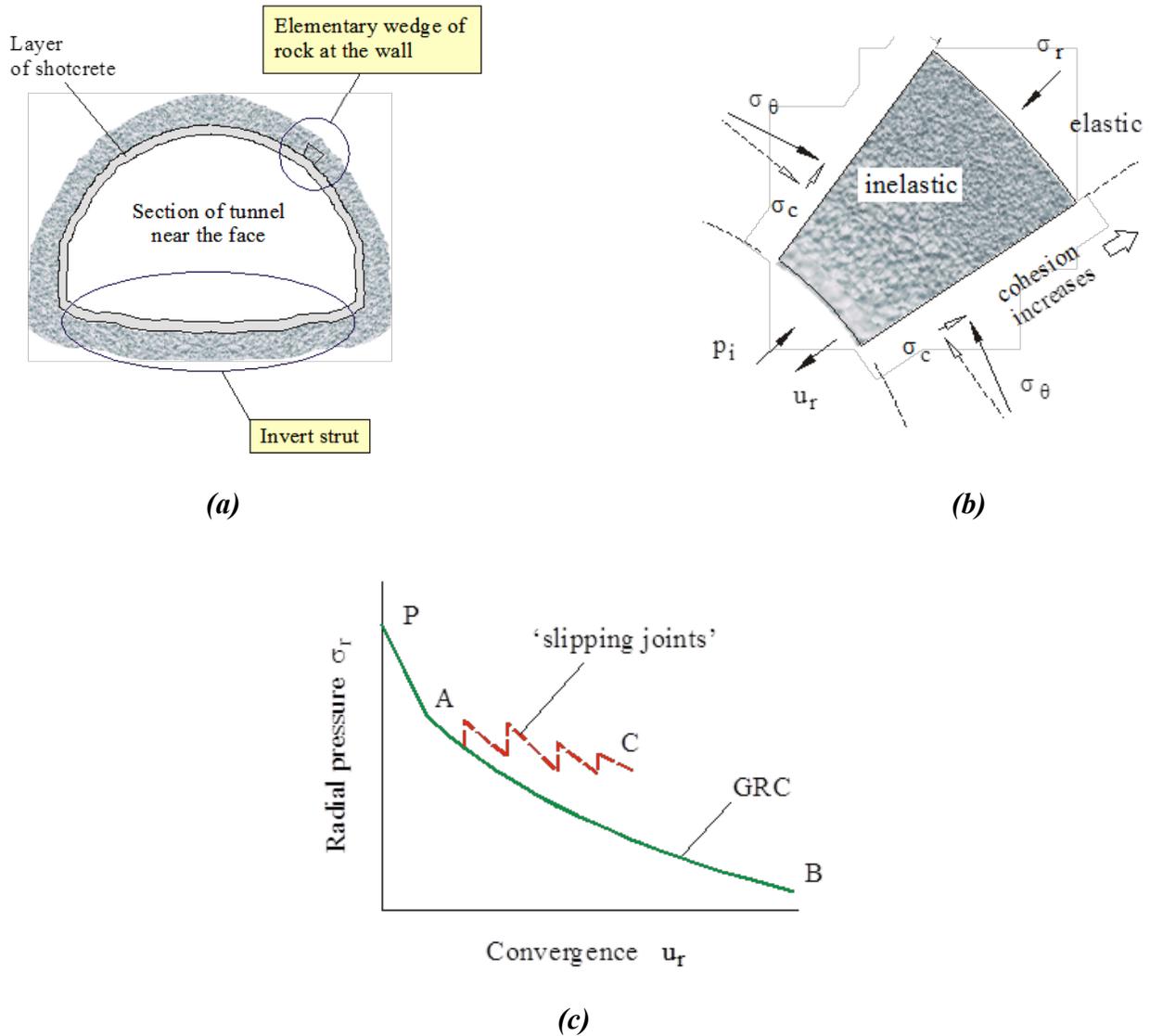


Figure 1. The New Austrian Tunneling Method (NATM)

³ The “XIII Colloquium of the International Society of Rock Mechanics in Salzburg, October 1962” was actually the XIII (Annual) Geomechanics Colloquium, Established in 1951 by a group of engineers, referred to as the ‘Salzburger Kreis’ (Salzburg Circle), to discuss rock mechanics issues, the Colloquium is now in its 66th year <https://www.oegg.at/en/geomechanics-colloquium-3/66th-geomechanics-colloquium-2017-79/> The International Society for Rock Mechanics (ISRM) <https://www.isrm.net/> was founded in Salzburg, May 1962 by Dr. Müller, a leading member of the Salzburg Circle.

The principle is illustrated in Figure 1. As soon as the tunnel wall is exposed after excavation, a layer of concrete is sprayed pneumatically around the periphery. This is followed by placement of an invert strut to develop an integral ‘ring’ (i.e. Rabcewicz’s ‘auxiliary arch’) around the complete excavation, as shown in Figure 1(a).

Figure 1(b) indicates the equilibrium of an elementary wedge at a specific location around the arch. Since the arch is not circular, the local radius of curvature changes around the periphery, and the scale (i.e. extent) of the elementary wedge will vary accordingly. Also the *in-situ* stresses acting on the wedge will, in general, vary around the periphery. This will also change the extent of the inelastic wedge. Even so, as long as the material in the inelastic region is able to support an increase in the tangential stress, σ_θ , as it displaces radially inwards (u_r) then the pressure (p_i) on the lining will decrease. In reality, the wedge is unlikely to be homogeneous; it may, for example contain joints or fractures across which the shear stress may rise to a limit that causes the joint to slip – decreasing the stress σ_θ , and increasing p_i . This behavior may recur several times as the wedge continues to displace inwards – as illustrated in Figure 1(c).

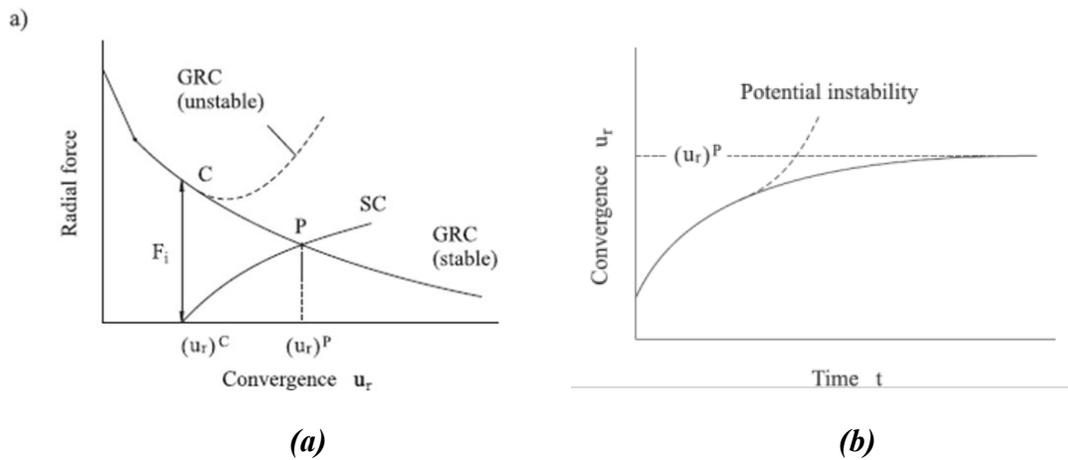


Figure 2. Stable and Unstable Deformation for an Element of a Tunnel Periphery.

Figure 2 illustrates the interaction between the inward displacement (convergence) u_r of an element of the tunnel periphery and the support provided by the element of lining at that location. The radial support required as the inelastic wedge develops is referred to as the Ground Reaction Curve (GRC). As noted earlier, if the wedge element is able to support an increasing stress difference ($\sigma_\theta - p_i$) as it displaces radially, then the GRC will follow a path tending towards stability. If slip or some other condition (e.g. pore collapse) intervenes, then σ_θ will decrease and the pressure (p_i) will rise, resulting in a potentially unstable situation. The force on the support will also rise as the inelastic wedge displaces inward – following the Support Characteristic path (SC). The difference F_i between the driving force exerted by the wedge (i.e. as indicated by the GRC) and the resisting force developed on the support (i.e. the SC) will determine the rate of inward displacement (convergence) of that element of the tunnel wall. It is sufficient, therefore, to monitor the rate of inward deformation of the tunnel at each location around the periphery to establish whether or not that element is moving towards a position of stability. If not, additional support (e.g., rock bolts, wire mesh, etc.) may be applied to that region to move the element towards a stable path. It is also critical that stability be established everywhere around the tunnel, -

instability and failure at any one location around the arch could potentially reduce the hoop stress around the entire arch, provoking the potential for instability and collapse everywhere.

The impressive element of the NATM procedure is that monitoring of the rate of inward deformation of the tunnel around the entire periphery can serve to ensure stability of the excavation, *even though the actual constitutive behavior of the rock at any point is unknown*. NATM is the classical example of the Observational Approach in rock engineering.

In the US, by contrast, tunnel supports were designed in the 1970's and 1980's using the Terzaghi Rock Load⁴ approach. Geotechnical engineers divided the tunnel length into different 'rock quality classes' in order to provide structural engineers with a constant load (force) created by a column of essentially detached rock in the roof of the tunnel, as the basis on which to design the steel support. Engineers of the US Army Corps of Engineers recognized the need to change to a design procedure similar to that of the NATM –and funded research to develop this change [Daemen, 1975] - but could not obtain approvals to make the change at that time. The NATM is now used widely in the US.

General Significance of the Observational Approach in Rock Engineering.

The Observational Approach to design in rock is a consequence of the variability and unpredictability of the precise constitutive behavior of a rock mass.

It is important to note

1. The initial estimate of the rock response to engineering, as used in NATM, is based on empirical rules derived from many years of experience in similar situations.
2. The essential element of this method is the possibility to make observations directly at the tunnel face.

For most of the newer 'borehole engineering' applications of Subsurface Engineering, neither of these features is available.

In considering many of the newer applications;

the uncertainty, variability and lack of data - features that are characteristic of engineering design in rock-remain.

How then can these new engineering challenges be addressed most effectively?

Advances are being made in assessing the validity of the empirical rules by application of numerical modeling techniques that are soundly rooted in Mechanics –but these rules apply to rock engineering in classical Civil and Mining Engineering. Some of these are applicable also to borehole technology, but most of the newer developments are essentially 'unchartered waters.'

Mention has been made earlier of one significant development the Synthetic Rock Mass (SRM) – (Newton in the Underworld, Figure 9 and associated discussion, in this issue of HF Journal)

⁴ Terzaghi, K. (1946). Rock defects and loads on tunnel supports. In R.V. Proctor and T. L. White (Eds.), *Rock tunneling with steel supports*, pp. 17–99. Commercial Shearing and Stamping Company. Youngstown, OH.

The Discrete Element Method is fully dynamic, so that the microseismic signals generated during modeling of the stimulation can be recorded, as in the field. Figure 3 shows one possible application, in which the Synthetic Rock Mass of a proposed Enhanced Geothermal System is stimulated following field procedures and the resulting microseismicity observed. Frequent ‘realizations’ the procedure in which the stimulation parameter are varied can provide important insights into the behavior of the overall EGS System. The current availability of powerful computational resources makes such modeling exercises realistic and worthwhile. Such exercises can help inform the planning of field operations and could lead eventually to procedures for real –time computer control of the stimulation and production operations. Such advances will not occur overnight and it would be wise to start computer stimulations without delay.

Further discussion of these ideas is presented in Pettitt et al; (2011)

Stones have begun to speak, because an ear is there to hear them.

Cloos,(1954) Conversation with the Earth. 4

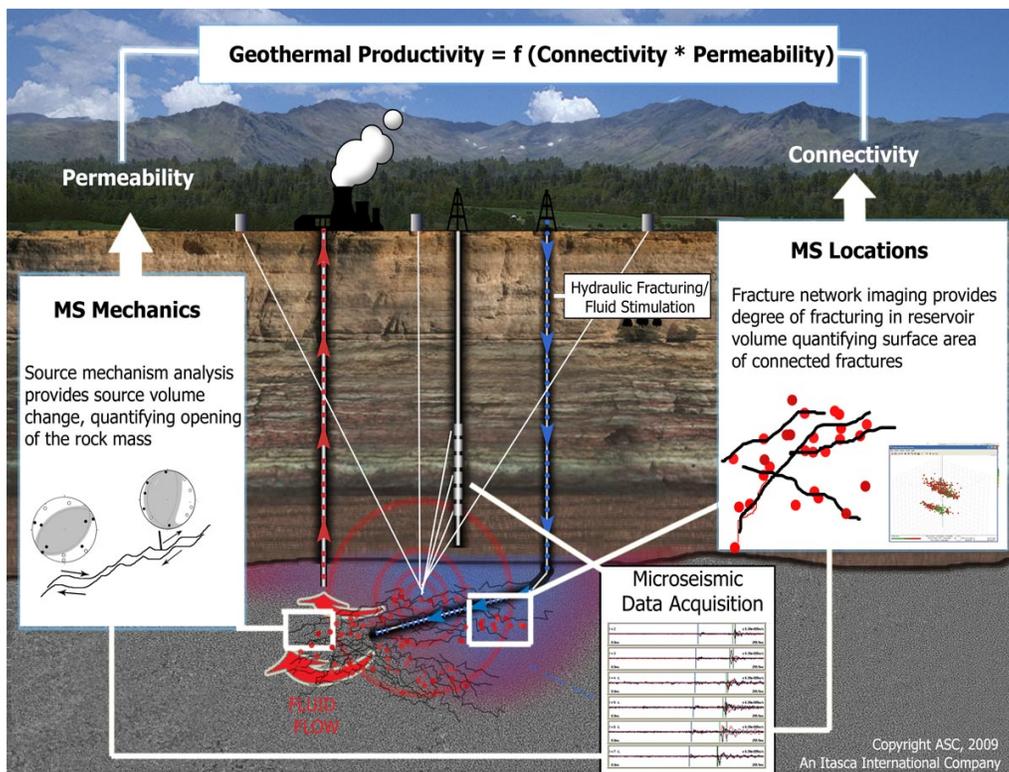


Figure 3. Fracture Network Engineering (Pettitt et al; 2011)

Fracture Network Engineering. Synthetic Rock Mass and Synthetic Seismicity Models are compared with observed microseismic signals for real –time control of fracture network development.

Clearly, there are limitations to this model. The parameters used to define the model are currently not generally available or especially well defined. Certainly there is considerable statistical variability and uncertainty associated with many of the parameters. In some cases e.g. tight shale formations, it is not

clear (at least to the writer) that DFN's are the controlling factor in determining how the rock mass responds to stimulation by hydraulic fracturing (See M. Vincent ⁵). Is it possible that Discrete Fractures generated to specific episodes of tectonic loading many millions of years in the past –and superimposed on the tightly bedded shale –may have healed, at least partially, in rocks with high clay-content, and hence are less significant in affecting fracture propagation than in crystalline rock. But insight into these and other questions can be gained through modeling – and could be a great help in designing the field studies.

The Geothermal Technologies Office (GTO) has taken a significant step forward by establishing the SubTER⁶ and FORGE⁷ initiatives.

The Big Idea: “Adaptive Control of Subsurface Fractures, Reactions and Flow”

ENERGY SECURITY

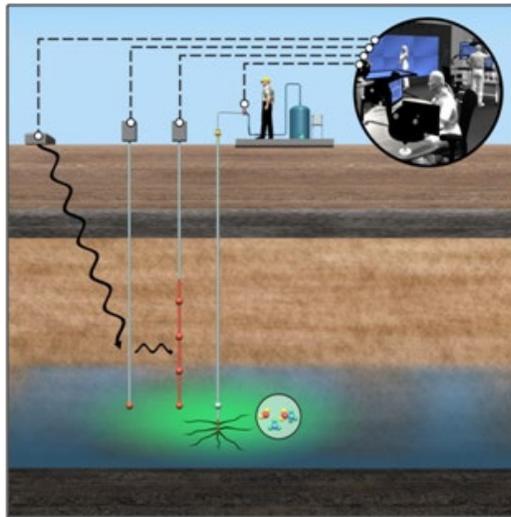
- Increase U. S. electrical production from geothermal reservoirs
- Increase U.S. unconventional oil and natural gas production

ENVIRONMENTAL SECURITY

- President's Climate Action Plan: Safely store CO₂ to meet GHG emissions reduction targets
- Safe storage/disposal of nuclear waste
- Reduced risk of induced seismicity
- Protect drinking water resources

ECONOMIC SECURITY

- Retain U. S. subsurface leadership
- Increase revenues (taxes and royalty) to Federal, State, and local governments
- Increased public confidence in subsurface energy sector



A Grand Challenge

Figure 4. Summary of US Dept. of Energy SubTER Initiative

(Slide Presented by Dr Marianne Walck Sandia Nat'l Lab.)

⁵ M.D.Vincent (2103) *Five Things You Didn't Want to Know about Hydraulic Fracturing* <http://cdn.intechopen.com/pdfs-wm/44148.pdf> Chapter 4 from HF 2013 <http://www.intechopen.com/books/effective-and-sustainable-hydraulic-fracturing>

⁶ <https://energy.gov/under-secretary-science-and-energy/subsurface-technology-and-engineering-rdd-crosscut>

⁷ <https://energy.gov/eere/forge/forge-home>

A parallel program that engages the talents of the US research universities and help establish a pool of graduates at the B.S, MS and Ph.D. levels is needed ‘

References

Cloos H. (1954), *Conversation with the Earth* (1954), Routledge and Keegan Paul 427p

Daemen, Jaak J.K. (1975) *Tunnel Support Loading Caused by Rock Failure*. Ph.D. Thesis. Univ. of Minnesota, Minneapolis, MN USA

Fairhurst, C., and C. Carranza-Torres.(2002) *Closing the Circle — Some Comments on Design Procedures for Tunnel Supports in Rock*, Proc. Univ. Minn. 50th Annual Geotechnical Conference (February 2002), pp. 21- 84. J. F. Labuz and J. G. Bentler, Eds. Minneapolis: University of Minnesota, 2002.

Fenner, R. (1938). *Untersuchungen zur erkenntnis des gebirgsdruckes*. Glückauf 74, 681–695 ;705–715.

Karakus, M. and R. J. Fowell (2004), *An Insight into the New Austrian Tunneling Method (NATM)*, Proc. 7th Regional Rock Mechanics Symp.(ROCKMEC '04), Sivas, Turkey, October 2004.
https://www.researchgate.net/publication/258224136_An_insight_into_the_New_Austrian_Tunnelling_Method_NATM

Labasse, H. (1949). *Les pressions de terrains dans les mines de huiles*. Revue Universelle des Mines. Liege, Belgium, Series 9, Vol. 5, No. 3, 78-88.

Panet, M. (1995). *Calcul des Tunnels par la Méthode de Convergence-Confinement*. Presse de l’Ecole Nationale des Ponts et Chaussées. Paris

Peck, R.B. (1969) *Advantages and Limitations of the Observational Method in Applied Soil Mechanics*. Géotechnique Vol.19: Issue 2.June 1969 pp171-187 DOI: <http://dx.doi.org/10.1680/geot.1969.19.2.171>
Published Online: May 25, 2015

Pettitt W. M.Pierce, B.Damajanac, J. Hazzard, L.Lorig, C. Fairhurst (2011) Itasca Consulting Group; I.Gil, M.Sanchez, N. Nagel (Itasca Houston); J Reyes-Montes, R. Paul Young (Applied Seismology Consultants.) *Fracture network engineering for hydraulic fracturing*. The Leading Edge August 2011 pp.844- 853

Rabcewicz, L. v (1964). *The New Austrian Tunnelling Method*, Water Power. Part 1, Nov 1964 pp. 453-457; Part 2, Dec. 1964 pp 511-515; Part 3, Jan. 1965 pp. 19-24;
<https://www.eoas.ubc.ca/courses/eosc547/lecture-material/Rabcewicz-NATM.pdf>

Terzaghi, K. (1946). *Rock defects and loads on tunnel supports*. In R.V. Proctor and T. L. White (Eds.), *Rock tunneling with steel supports*, pp. 17–99. Commercial Shearing and Stamping Company. Youngstown, OH.